


LLRF 2013

Development and Test of Digital LLRF Control Procedures and Techniques in Scope of ILC

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Contents

Superconducting RF Test Facility (STF) Quantum Beam Project (QBP)

STF

- Development and demonstration of high gradient superconducting accelerator technology aimed for ILC

Normal conducting photo-cathode RF gun*
(5 MW Klystron on ground level)

KEK

STF

QBP

Two superconducting 9-cell cavities within capture cryomodule (CCM)
(800 kW klystron in the tunnel)*

Beam dump

Optical cavity for X-ray creation

X-ray detector

*operated using digital LLRF control techniques

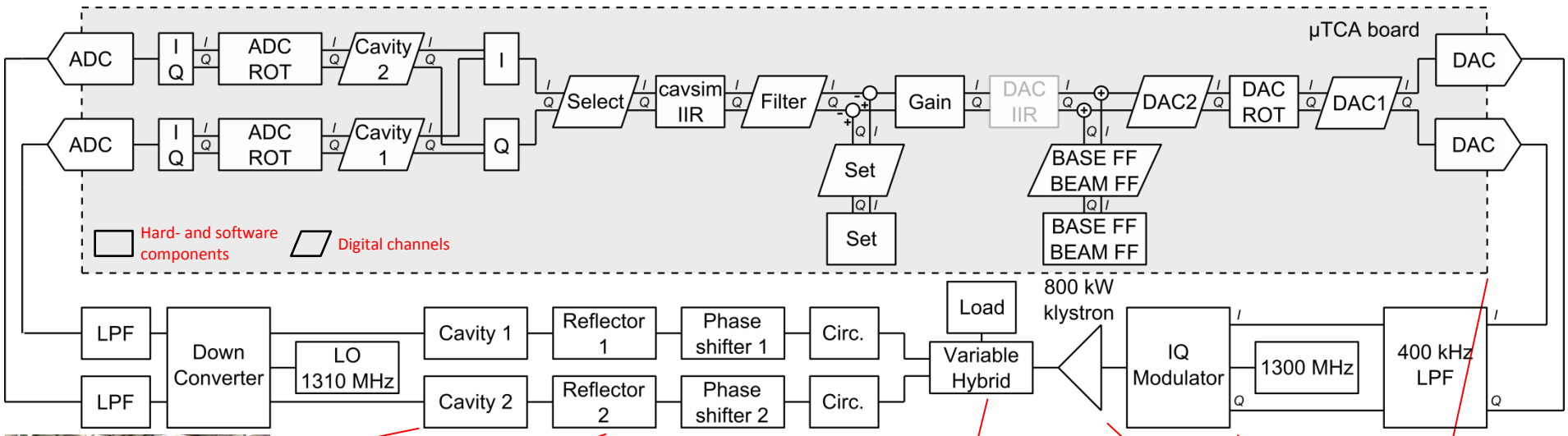
QBP

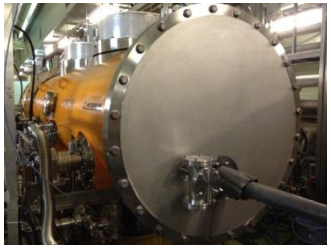
QBP

- Demonstration of high brightness X-ray generation by inverse laser Compton scattering.

Cavity gradient:	*20±20% MV/m*		
Loaded Q:	*3e6*	*Bunch number:*	*162500*
Bunch number:	*162500*	*Bunch spacing:*	*162.5 MHz*
Operation mode:	*pulsed*	*Beam current:*	*10 mA*
Repetition rate:	*5 Hz*	*Energy:*	*40 MeV*
Pulse length:	*1 ms*	*Charge:*	*62 pC*

LLRF Control Loop

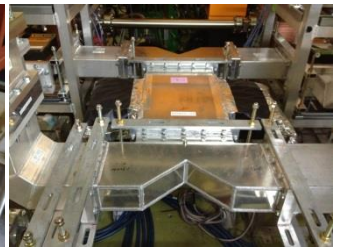




Capture cryomodule
(2 SC cavities)

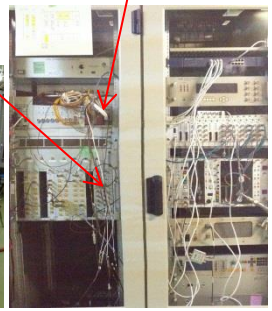
Reflector
(Q_L adjustment)

Phase shifter
(cavity phase)



Variable hybrid
(RF power ratio)

800 kW klystron
(RF power creation)



19-inch rack

Contents

Nominal Operation

RF Parameter

V_{Cav1} = 16 MV/m

V_{Cav2} = 24 MV/m

Q_{L1} = 3e6

Q_{L2} = 3e6

Filling time = 540 µs

*Beam compensation active

Beam Parameter

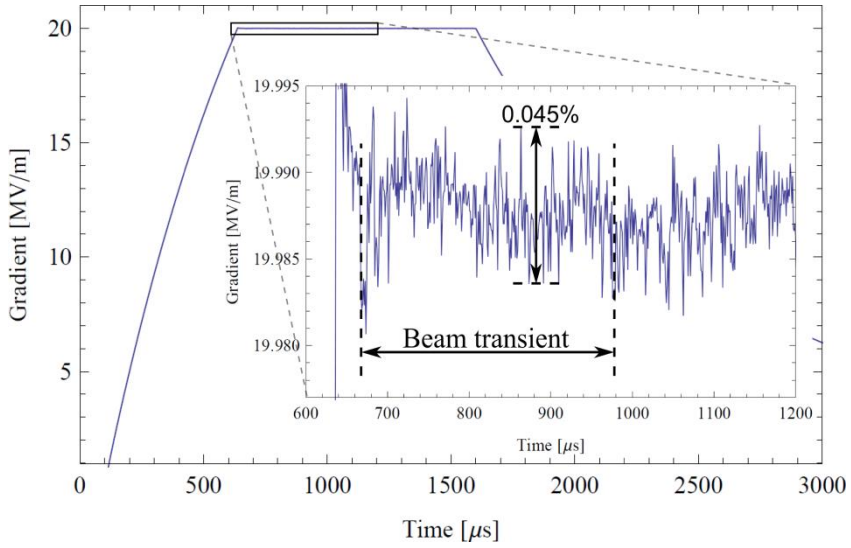
Pulse Length = 615 µs

Current = 6.6 mA

ILC Stability Requirements

ΔA/A = 0.07%

Δϕ = 0.24°



Beam	6.6mA* (60 mins)	Off (20 mins)
ΔA/A (cav1)	-	0.042%
ΔA/A (cav2)	-	0.045%
ΔA/A (vector sum)	0.009%	0.008%
Δϕ (cav1)	-	0.027°
Δϕ (cav2)	-	0.021°
Δϕ (vector sum)	0.009°	0.008°

All stabilities are estimated for the beam transient time.

Contents

High Q_L Operation

ILC requirements

- Operation intended at Q_L values in a range of 3e6 to 10e6

- Bandwidth becomes very narrow (e.g. 32Hz at Q_L=2e7), detune becomes severe
- Microphonics maybe problematic to deal with
- Demonstration only possible at KEK STF due to wide Q_L range (2e6~5e7)

→ Q_L adjustment with waveguide reflectors
Automated detune compensation via piezo tuners

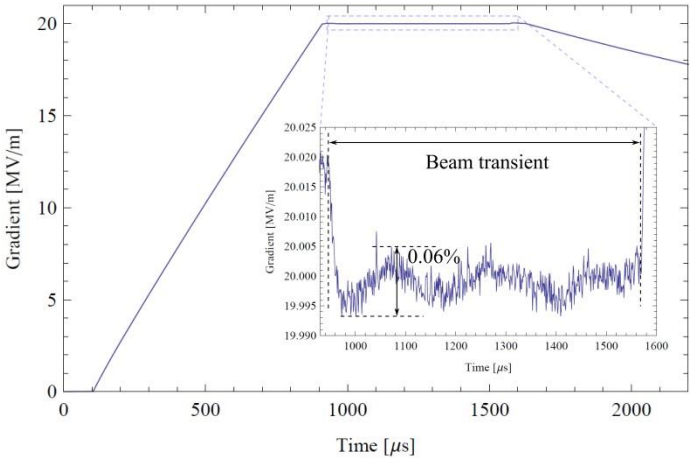
High Q_L Operation

RF Parameter

V_{Cav1} = 20 MV/m
V_{Cav2} = 20 MV/m
Q_{L1} = 2e7
Q_{L2} = 2e7
Filling time = 800 µs
*Beam compensation active

Beam Parameter

Pulse Length = 615 µs
Current = 6.1 mA



	High Q_L		Nominal	
Beam	6.1 mA* (60 mins)	Off (20 mins)	6.6 mA* (60 mins)	Off (20 mins)
ΔA/A (cav1)	0.121%	0.030%	-	0.042%
ΔA/A (cav2)	0.160%	0.032%	-	0.045%
ΔA/A (vector sum)	0.011%	0.008%	0.009%	0.008%
Δϕ (cav1)	0.033°	0.027°	-	0.027°
Δϕ (cav2)	0.028°	0.027°	-	0.017°
Δϕ (vector sum)	0.015°	0.014°	0.009°	0.008°

All stabilities are estimated for the beam transient time.

- Detuning stayed constant during 1h operation
  → Microphonics are not severe
- Fulfills ILC stability requirements (ΔA/A = 0.07%, Δϕ = 0.24)

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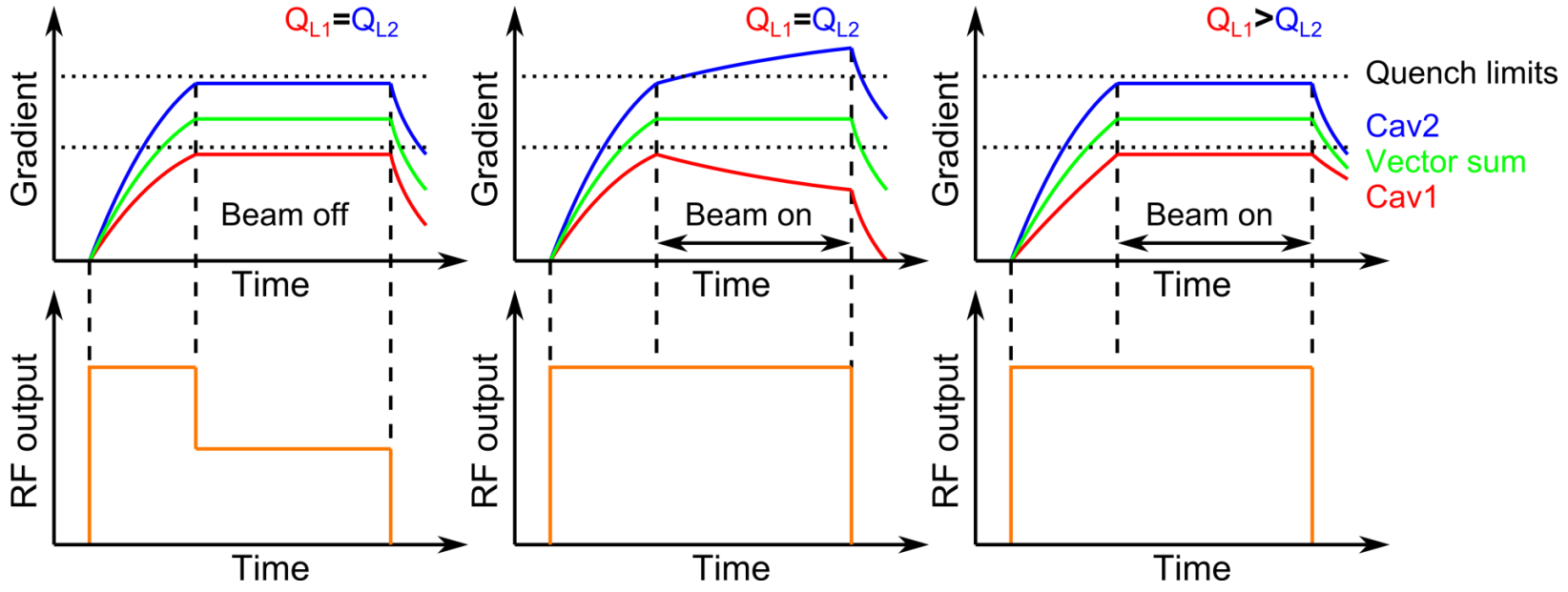
- Introduction
- Nominal Operation
- High QL Operation
- Fully Automated PkQL Control for ILC-like Operation
- Near Klystron Saturation Operation
- Klystron Linearization
- Summary

P_kQ_L Control

Target: Operation with flat flattops

- Stable beam acceleration (Cavity gradient tilts and RF fluctuations induce transverse beam orbit changes)
- High gradient operation near quench limit during whole flattop for all cavities

Operation of multiple cavities driven by a single klystron combined with beam loading leads to gradient tilts → **P_kQ_L Control**



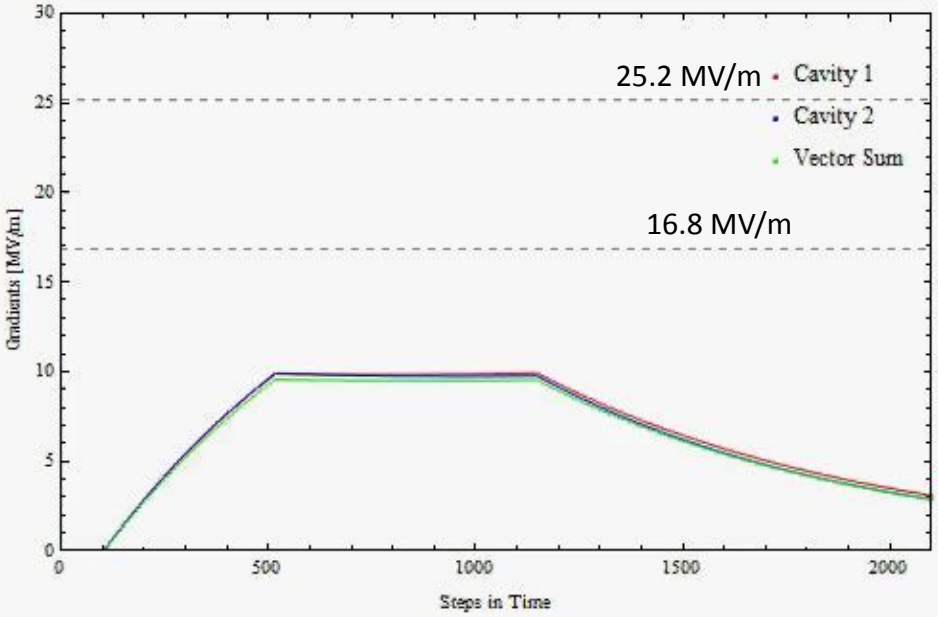
P_kQ_L Control Goal

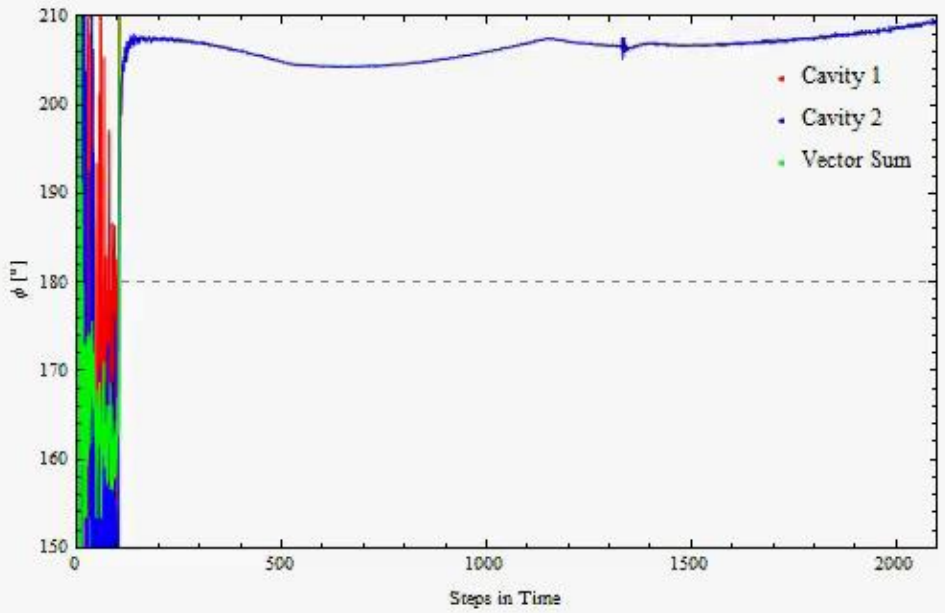
ILC requirements

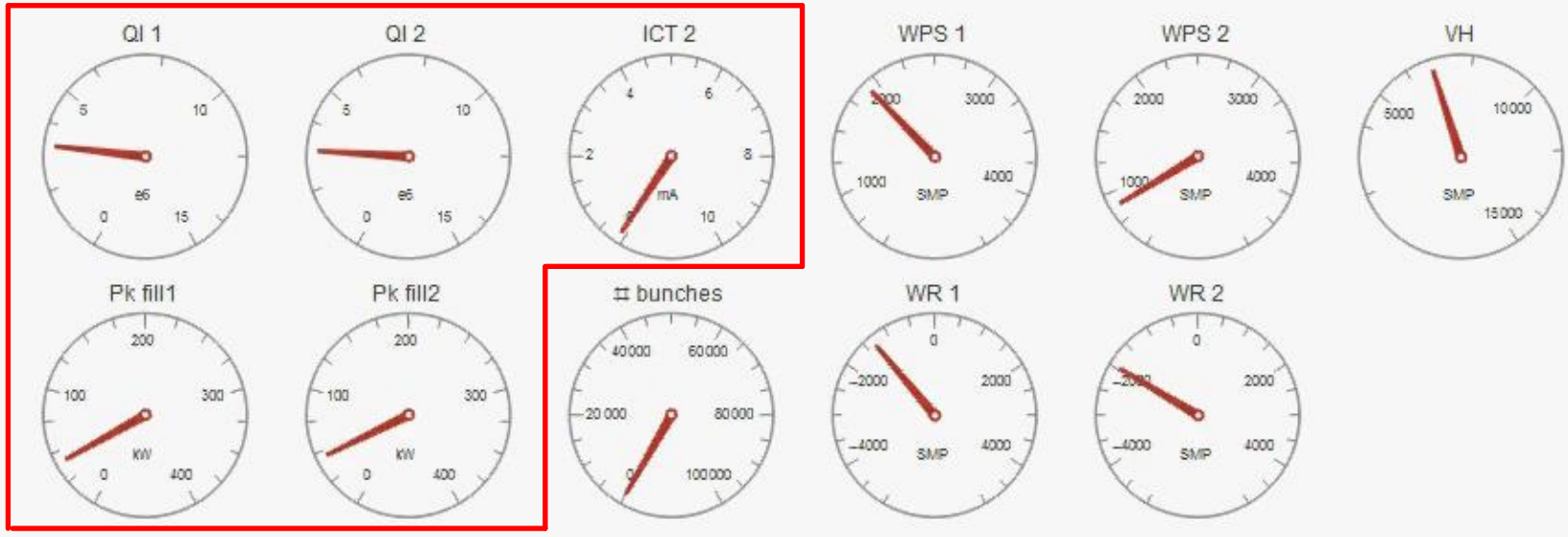
- Fully automated P_kQ_L operation (~16000 cavities)
- Cavity gradient spread ±20% (e.g. 16 MV/m and 24 MV/m)
- Cavity gradients 5% below of respective quench limits
- Cavity gradients must never exceed quench limits
- Cavity vector sum stabilities $\Delta A/A = 0.07\%$ and $\Delta\phi = 0.24°$

Steps to engage in P_kQ_L operation

- Determination of working point for adjustment of cavity RF input powers (P_k) and Q_L values respective to the beam current
- Fully automated P_kQ_L setting procedure


25.2 MV/m
16.8 MV/m
Cavity 1
Cavity 2
Vector Sum
Gradients [MV/m]
Steps in Time


Cavity 1
Cavity 2
Vector Sum
ϕ [°]
Steps in Time


QI 1
QI 2
ICT 2
WPS 1
WPS 2
VH
Pk fill1
Pk fill2
bunches
WR 1
WR 2
e6
mA
kW
SMP

PkQL Operation Stabilities

RF Parameter

V_{Cav1} = 16 MV/m

V_{Cav2} = 24 MV/m

Q_{L1} = 9e6

Q_{L2} = 3e6

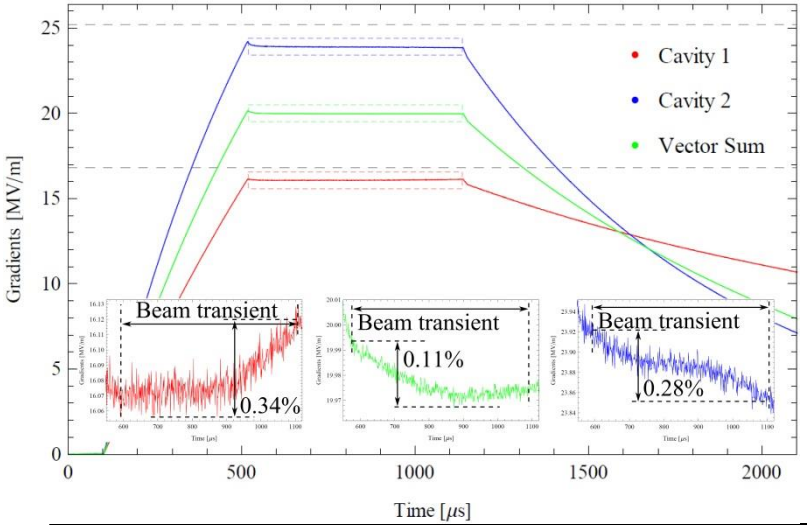
Filling time = 410 µs

*Beam compensation active

Beam Parameter

Pulse Length = 615 µs

Average current = 6.4 mA



	PkQL	Nominal	
Beam	6.4 mA* (60 mins)	6.6 mA* (60 mins)	Off (20 mins)
ΔA/A (cav1)	0.041%	-	0.042%
ΔA/A (cav2)	0.031%	-	0.045%
ΔA/A (vector sum)	0.009%	0.009%	0.008%
Δϕ (cav1)	0.042°	-	0.027°
Δϕ (cav2)	0.031°	-	0.021°
Δϕ (vector sum)	0.009°	0.009°	0.008°

All stabilities are estimated for the beam transient time.

- First actual PkQL operation
- Vector sum stabilities comparable with nominal operation
- Fulfills ILC stability requirements (ΔA/A = 0.07%, Δϕ = 0.24)

Contents

Near Klystron Saturation Operation

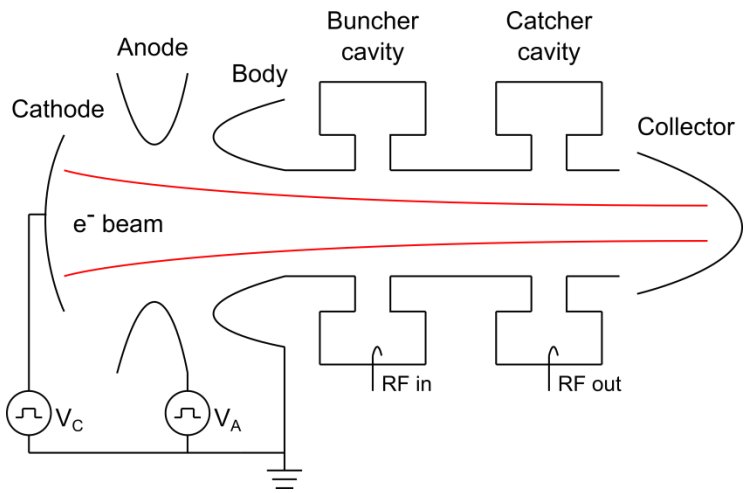
ILC requirements

- Operation within 5% of klystron saturation

- Save power (all power always goes to the collector)
- Reduce operating costs (water cooling)

Klystron for SCCs at STF

- Toshiba E37501
- 800 kW
- Triode-like tube



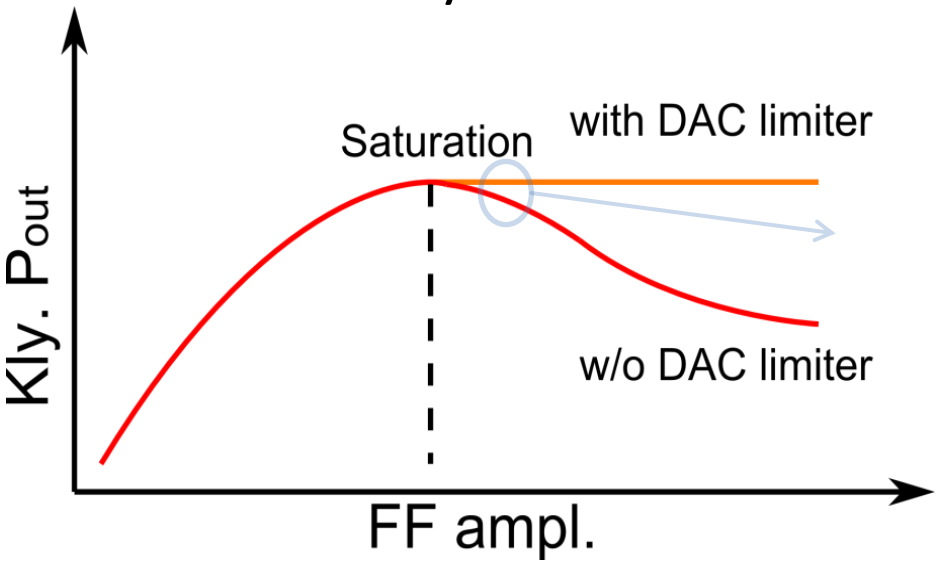
Suppression of Overdrive

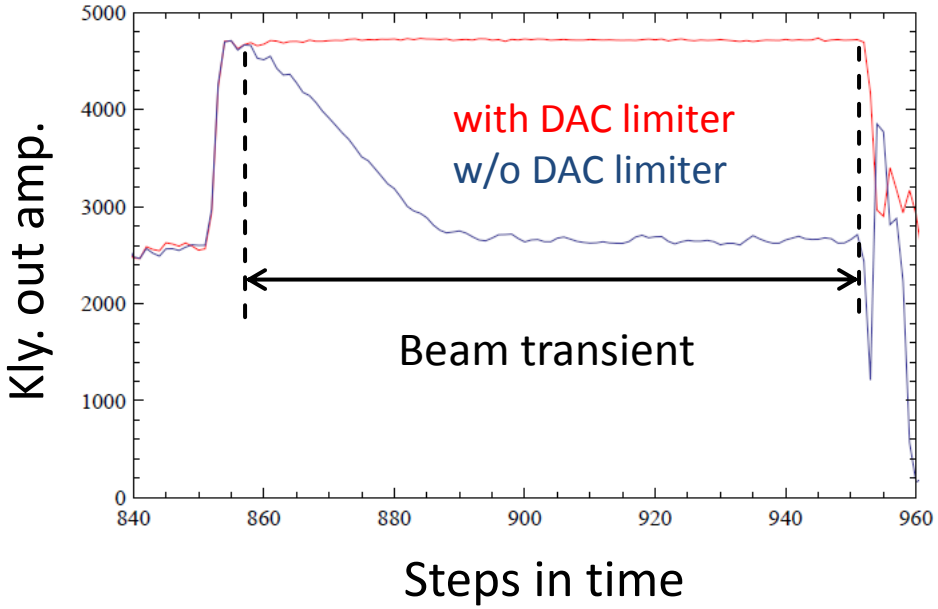
At STF QB project

- DAC limiter rectangular in I and Q plane
- ±I and ±Q limits can be set individually

RF Parameter
V_{Cav1} = 16 MV/m
V_{Cav2} = 24 MV/m
Q_{L1} = 3e6
Q_{L2} = 3e6
Filling time = 523 µs
HV = 49 kV

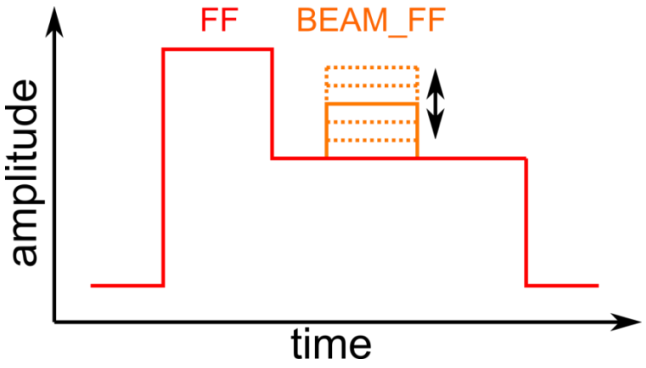
Beam Parameter
Pulse Length = 100 µs
Average current = 5.9 mA

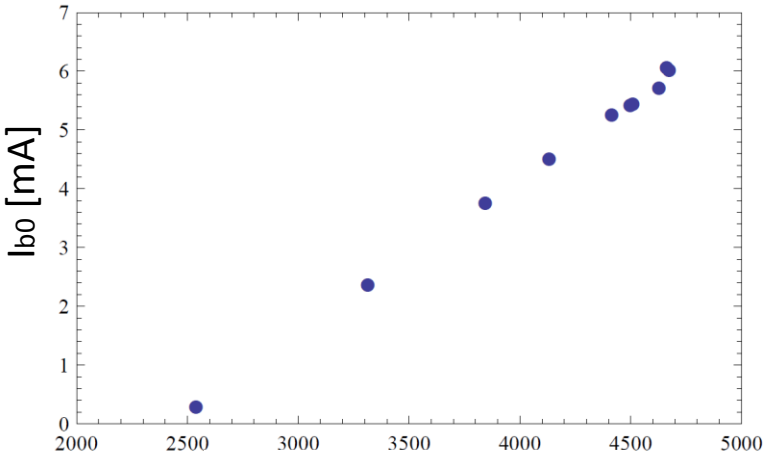




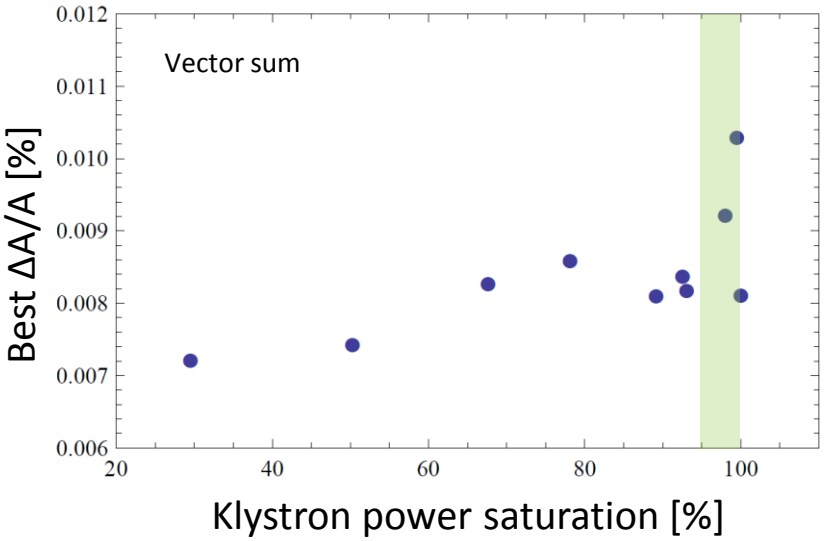
Stabilities Near Klystron Saturation

Feedforward beam compensation

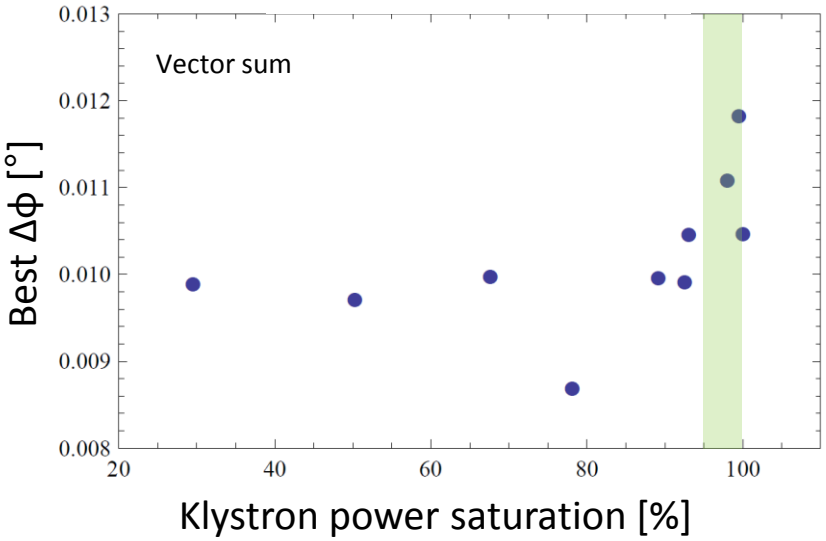




Vector sum amplitude



Klystron power saturation [%]



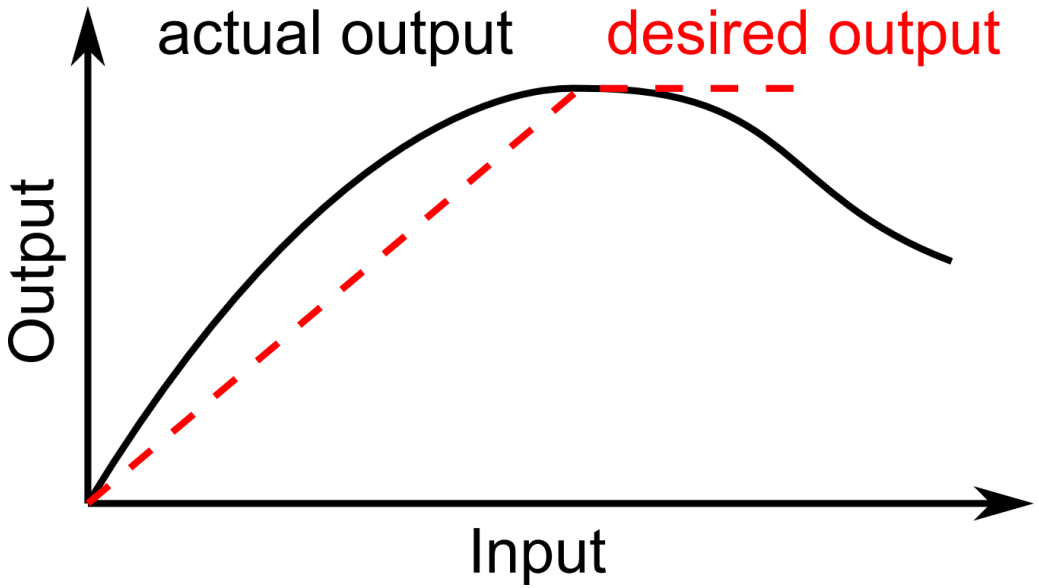
Klystron power saturation [%]

ILC Stability Requirements
ΔA/A = 0.07%
Δϕ = 0.24°

All stabilities are estimated for the beam transient time.

Contents

Target of Klystron Linearization



Actual output: Non-linear & oversaturation

Desired output: Linear & constant at saturation point

- Klystron linearization (non-linear) and klystron (non-linear) → linear output
- Amplitude limitation

Principle

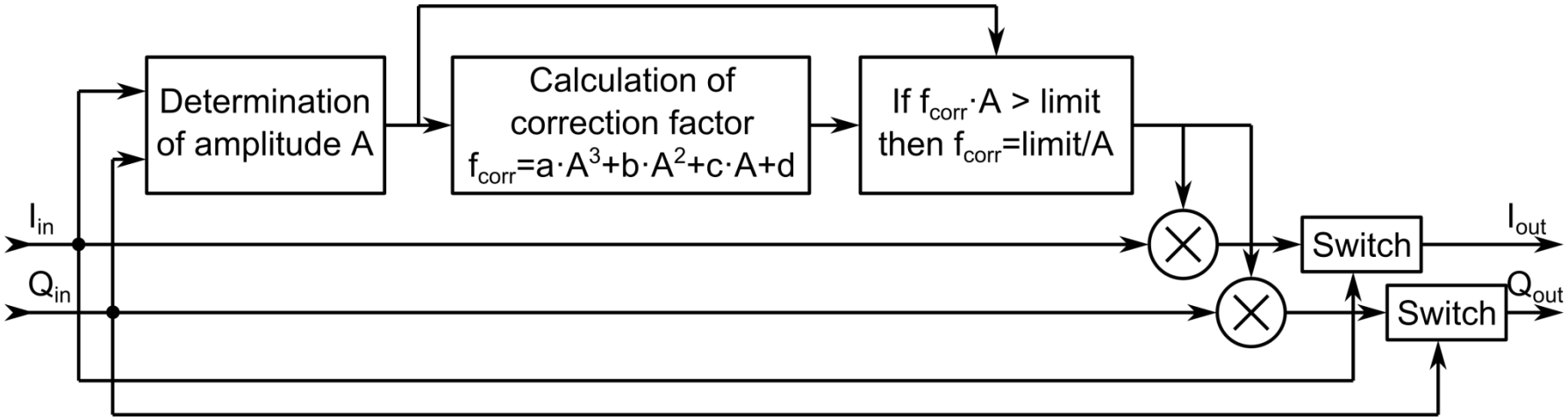
Requirements:

- 3rd order correction function for calculation of correction factor
- Limiter circular in I and Q plane
- On/Off switch

Configuration parameter:

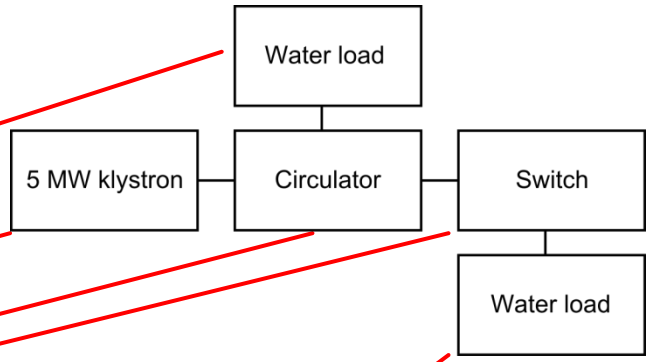
- a, b, c, d (for correction factor function)
- l (limit)
- sw (On/Off switch)

- Addition to loop delay as low as possible
- In case of switch off no additional loop delay
- For superconducting cavities



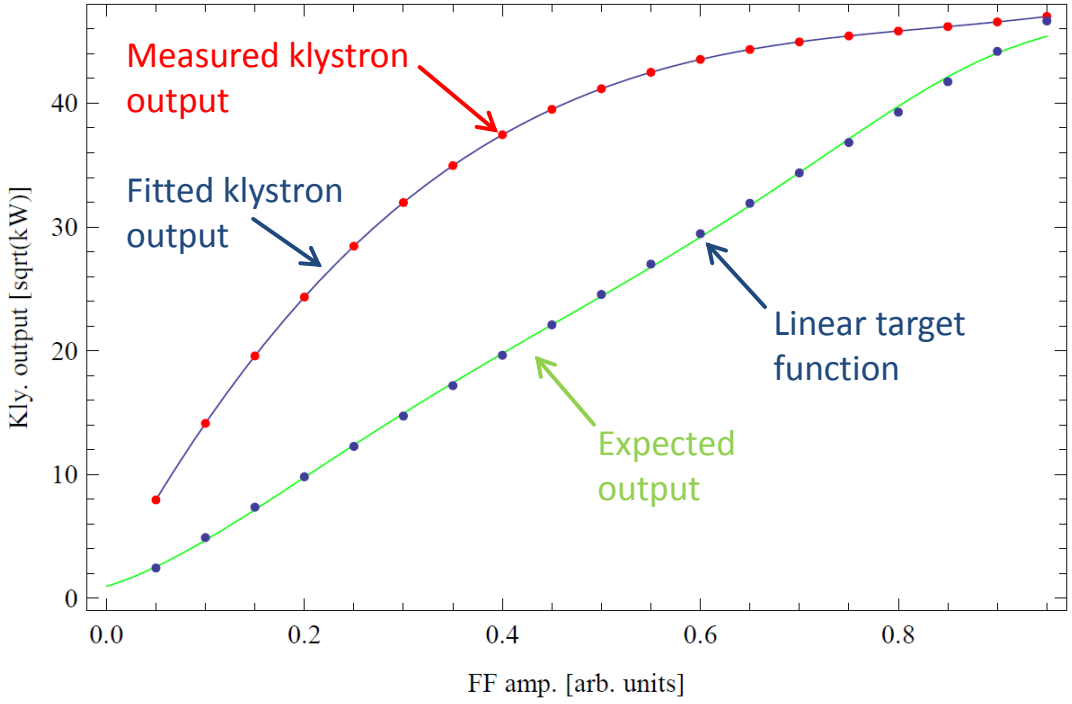
Test Setup at Fermilab NML

Running the 5 MW klystron into the water load



Estimation of Parameters

Using Mathematica



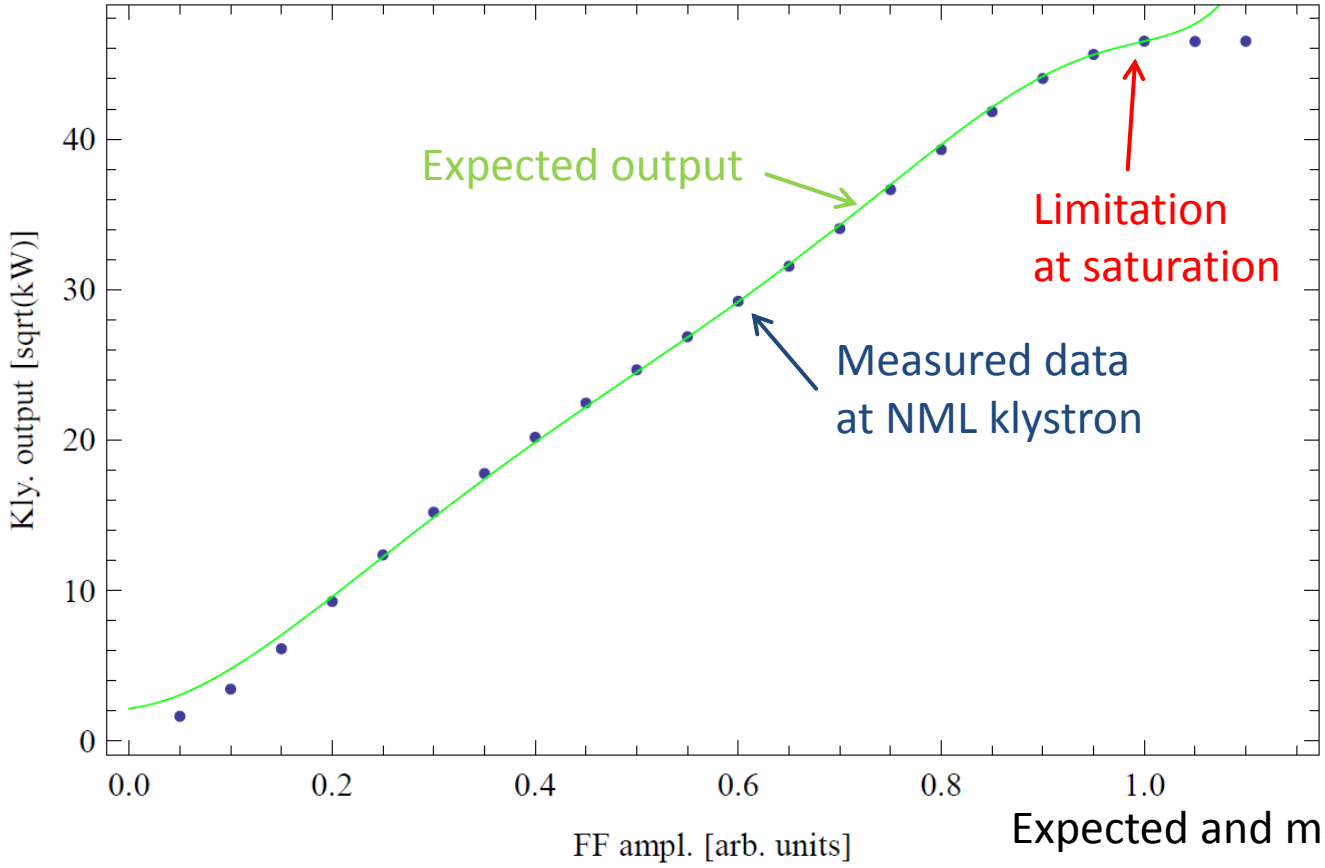
- Recorded klystron output w/o kly. lin. (feedforward amplitude scan)
- Fit to klystron output
- Estimation of linear target function
- Fit to target function for parameter estimation

Parameter	Value
a	1.91
b	-2.38
c	1.19
d	0.16

- Limit estimated by point of saturation

Test at NML - Result

Comparison of FF Amplitude Scan at NML
and expected output due to fit in Mathematica



Expected and measured
klystron outputs agree well ✓

Contents

Summary

- STF / Quantum beam project
- Digital LLRF feedback loop
- Stabilities for long time nominal operation were evaluated with and without beam
- Even under high QL (2e7) operation the stabilities were comparable to nominal operation
- First full automated ILC-like PkQL operation was demonstrated with stabilities comparable to nominal operation

Summary

- A near klystron saturation study showed that stable operation within 5% of klystron saturation is possible in case of mached beam current
- Successful development and test of klystron linearization at NML, measured klystron output agrees well with expected output

Questions?

Thank you very much for your attention!